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HTML ABSTRACT

Controlling Light Pulses and Light Beams with Photonic Band-Gap Structures

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Abstract. Pulse compression, second-harmonic generation, and spectral broadening of short light pulses in photonic crystals are discussed. The abilities of such structures to guide and localize light, phase-match nonlinear interactions, and to generate evanescent waves are explored.

1. INTRODUCTION

Remarkable properties of photonic crystals [1 – 3], or photonic band-gap (PBG) structures, are widely discussed now in the context of the control of radiative processes [1], creation of new optical components, including optical delay lines [4], switches [5 - 7], narrow-band filters and ultradispersive prisms [8], light guiding and bending [9], and even the entanglement of atomic states and quantum computations [10]. However, in spite of rapidly growing applications of photonic crystals, or photonic band-gap (PBG) structures, the nonlinear-optical aspect of the problem and all the exciting opportunities offered by photonic crystals in the interesting and highly promising area of short-pulse generation and control are still to be adequately explored and understood. Similar to conventional nonlinear crystals, which revolutionized the nonlinear optics in the 1960, becoming a routine tool of nonlinear-optical experiments nowadays, nonlinear photonic crystal seem to offer much promise for the conceptual and technical progress in various fields of modern optics. Ideas of nonlinear-optical diodes [11] and switches [5 – 7], compact pulse compressors [12], and frequency doublers [13, 14] have been actively discussed in the last few years, revealing a high potential of such devices both for fundamental studies and applications. This agenda of reworking the nonlinear optics of conventional crystals for photonic band-gap structures seems to be a challenging problem for the physics of the twenty first century, promising many rewards in the nearest future.

The purpose of this lecture is to demonstrate that the remarkable abilities of PBG structures to localize light and locally enhance light fields, along with their unique dispersion properties, make photonic crystals very useful for various applications in

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ultrafast photonics and nonlinear optics, including the formation of very short light pulses, the control of the phase and the duration of such pulses, and the enhancement and phase-matching of nonlinear-optical interactions. The material of this lecture is based on the results of experimental and theoretical studies of photonic crystals carried out by our group at Physics Faculty and International Laser Center, M.V. Lomonosov Moscow State University, in collaboration with several groups in Russia and abroad. The plan of this lecture is the following. In Section 2, we will show that dispersion properties of one-dimensional photonic crystals can be employed to efficiently control the phase of ultrashort pulses and to create compact pulse compressors. Section 3 demonstrates that one-dimensional PBG structures allow phase and group-velocity matching to be achieved for second-harmonic generation with short light pulses. The properties of field localization in a 2D PBG structure with a defect of a photonic-crystal lattice and possible nonlinear-optical applications of this effect will be discussed in Section 4. The results of experiments with optical fibers whose cladding has a form of a 2D PBG structure with a pitch ranging from 0.47 to 3.2 μm are presented in Section 5. Finally, our main inferences are summarized in the Conclusion.

2. SHORT PULSES IN PBG STRUCTURES: PULSE CHIRPING AND COMPRESSION

Optics of short light pulses is one of the most exciting and rapidly growing areas of modern physics. The methods developed recently for the generation of light pulses with durations corresponding to a few cycles of the light field [15] open up new opportunities in the investigation of ultrafast processes and ultrashort-pulse optical technologies. Dispersion properties of PBG structures seem to be of considerable interest in this context, as the high dispersion attainable with such structures allows efficient compression to be implemented within small propagation lengths, thus permitting the creation of compact all-solid state pulse compressors, and pulse distortions due to higher order dispersion to be avoided by chirping the PBG structure.

2.1. The General Idea

We shall illustrate this approach by considering a simple model of a one dimensional PBG structure consisting of alternating dielectric layers with thicknesses a and b and refractive indices n_a and n_b, respectively. As shown in [12], such a model allows some important features of short-pulse propagation through PBG structures to be understood on the qualitative level.

Consider a phase-modulated Gaussian light pulse

$$A_0(t) = \rho_0 \exp\left[-\frac{1}{2}(\tau_0^{-2} + i\alpha_0)t^2\right], \quad (1)$$

where τ_0 is the characteristic pulse duration and α_0 is the rate of frequency modulation, propagating along the x-axis in the considered 1D PBG strutcure. Within the framework of approximation of slowly varying envelopes with allowance for second-order dispersion, the evolution of the pulse duration in this case is written as [16]

$$\tau_p(x) = \tau_0 \sqrt{(1-\alpha_0 k_2 x)^2 + (k_2 x / \tau_0^2)^2}\ , \quad (2)$$

where $k_2 = \partial^2 k / \partial \omega^2$ is the group-velocity dispersion, which can be calculated with the use of an expression governing dispersion of the considered one-dimensional PBG structure as a whole [17],

$$\cos(kd) = \cos(\frac{\omega}{c} n_a a)\cos(\frac{\omega}{c} n_b b) - \frac{n_a^2 + n_b^2}{2 n_a n_b} \sin(\frac{\omega}{c} n_a a)\sin(\frac{\omega}{c} n_b b). \quad (3)$$

Here, ω is the frequency of the light wave, c is the speed of light, and $d = a + b$ is the lattice constant.

As can be seen from formula (2), in regions where $\alpha_0 k_2 > 0$, the duration of an initially chirped pulse first decreases, reaches its minimum value, and then grows. The estimates performed with formulas (1) – (3) (see [12] for the details) show that photonic crystals allow one to implement efficient compression of femtosecond pulses within a characteristic spatial scale of less than a millimeter. Therefore, PBG structures hold much promise as elements of compact femtosecond laser systems.

Obviously, the approach employed above gives only a general impression of short-pulse evolution in a 1D PBG structure. A more rigorous analysis is required to take into consideration higher order dispersion effects and to see what may happen to a pulse in the neighborhood of the photonic band gap. Such a numerical analysis was performed in [12, 18]. The algorithm of simulations can be briefly described as follows. A light pulse at the input of a photonic crystal is represented as a wave packet in terms of the Fourier integral in frequency domain by means of fast Fourier transform (FFT). Upon the completion of the forward FFT procedure, the amplitudes of electromagnetic waves transmitted through the photonic crystal are calculated for each Fourier component with the use of the transfer-matrix scheme where direct multiplication of transfer matrices is replaced by recurrent computation of the relevant determinants (see the details in [12, 18]). At the final stage, inverse FFT is performed to reconstruct the pulse transmitted through the photonic crystal in time domain.

The results of numerical simulations show that, with an appropriate choice of the initial chirp of the laser pulse, efficient pulse compression can be implemented due to the compensation of the chirp in the process of propagation of such a pulse in a photonic crystal with minimum distortions of the pulse waveform. Varying parameters of a PBG structure (the lattice constant d, the filling ratio a/d, and the ratio of the refractive indices of materials constituting a photonic crystal), we can effectively control the dispersion of a photonic crystal and, thus, implement chirp control of short light pulses, which provides an opportunity to compress laser pulses in a controllable fashion within extremely short propagation lengths. According to the results of numerical simulations, a chirped laser pulse with an initial duration $\tau_0 = 10T_0$, $\lambda = 800$

nm, and $\alpha_0 = -2/(\tau_0)^2$ can be compressed in a photonic crystal with $d = 460$ nm, $a/b = 0.3$, $n_a = 1.5$, $n_b = 1.0$ (which corresponds to anomalous group-velocity dispersion) to $5.5T_0$, $5T_0$, and $5.5T_0$ within the lengths of 127, 253, and 380 μm, respectively. For an optimized PBG structure, the results of numerical simulations for the length of maximum compression, the minimum pulse duration, and the evolution of time duration along x agree well with predictions of second-order dispersion theory for slowly varying envelopes. However, the accuracy of approximation (1) – (3) is insufficient to describe the evolution of a laser pulse when the pulse duration is on the order of several periods of the optical field and to take into account high-order dispersion effects, which may considerably distort the waveform of a light pulse emerging from a photonic crystal [12, 18].

2.2. Nonlinear PBG Pulse Compressors

We have demonstrated above that dispersion properties of photonic crystals allow the chirp of a short light pulse to be compensated in a controllable fashion, permitting an efficient compression of femtosecond pulses within a characteristic spatial scale of less than a millimeter. The next step is to put a chirp on a pulse within the PBG structure. This can be done through self-phase modulation if one of the materials (or both materials) employed to fabricate a PBG structure possess cubic optical nonlinearity. In what follows, we will demonstrate that such a PBG structure not only allows chirp compensation, but also provides an opportunity to compress chirp-free pulses. A PBG pulse compressor of this type consists of alternating nonlinear-optical layers with thicknesses a and b and dielectric constants

$$\varepsilon_a = \varepsilon_{0a} + \varepsilon_{nl}|E|^2 \quad (4a)$$

and

$$\varepsilon_b = \varepsilon_{0b} + \varepsilon_{nl}|E|^2, \quad (4b)$$

respectively, where E is the amplitude of the laser field. Such a device combines dispersion properties characteristic of PBG structures with the possibility of nonlinear-optical transformation of the spectrum of a laser pulse. Propagating in such a medium, a laser pulse experiences a spectral broadening due to self-phase modulation (SPM). With an appropriate choice of the sign of the product of the relevant cubic susceptibility and the group-velocity dispersion, the SPM-induced chirp is compensated in such a system, which makes it possible to implement true compression of light pulses. Note that the possibility of pulse compression due to the simultaneous action of self-phase modulation and dispersion of a periodic structure has been demonstrated both theoretically [19] and experimentally [20] for Bragg structures. However, analysis of pulse compression in such structures was restricted to the approximation of slowly varying envelopes. In addition, an important difference of PBG structures, as compared with Bragg structures, stems from the fact that PBG structures are characterized by much higher contrasts of refractive indices, which

makes it possible to implement compression at much shorter spatial scales but requires much more careful analysis of nonlinear effects.

Pulse compression in a PBG structure with a cubic nonlinearity of the form (4a) – (4b) can be achieved when (e.g., see [16])

$$\varepsilon_{nl}\frac{\partial^2 k}{\partial\omega^2} < 0, \quad (5)$$

i.e., within sections of anomalous dispersion if $\varepsilon_{nl} > 0$ and within sections of normal dispersion if $\varepsilon_{nl} < 0$. Although analytical expressions for pulse self-compression derived within the framework of second-order dispersion theory for light pulses with slowly varying envelopes make it possible to determine conditions for pulse compression and even to estimate characteristic parameters of pulse compression in photonic crystals, they do not provide an adequate description of higher order dispersion effects and become inapplicable for laser pulses comprising several tens of optical cycles.

Numerical simulations for light pulses propagating in a PBG structure with embedded optical nonlinearity were carried out with the use of a nonlinear finite-difference time-domain technique (FDTD) [21], which implies a direct time integration of the Maxwell equations incorporating nonlinear effects originating from the intensity-dependent addition to the dielectric constant (4a) – (4b). Figure 1 shows the evolution of the spectrum and the envelope of a short laser pulse with a wavelength of 800 nm and $\tau_0 = 10T_0$ propagating in a one-dimensional PBG structure with $a = b$, $\varepsilon_{0a} = 1$, $n_0 = \sqrt{\varepsilon_{0b}} = 1.5$, $d = 415$ nm, and the intensity-dependent addition to the dielectric constant $\xi = \varepsilon_{nl}|E|^2 = 0.01$. The dependence of parameter k_2 on the wave number and the frequency range where group-velocity dispersion of a PBG structure ensures self-compression of an SPM-chirped light pulse (i.e., condition (5) is satisfied) are shown at the top of Fig. 1. The duration of a light pulse emerging from a nonlinear PBG structure is limited from below by the width of the spectral range of pulse self-compression. Beyond this range, a part of the spectrum of an SPM-chirped laser pulse falls either within a stop band or within a domain where group-velocity dispersion leads to pulse spreading rather than to pulse compression (the evolution of the spectrum E_ω of an SPM-chirped pulse propagating in a PBG structure is illustrated at the left of Fig. 1). In such a situation, the waveform of the laser pulse displays considerable distortions (the evolution of the waveform of an SPM-chirped pulse propagating in a PBG structure is shown at the right of Fig. 1). An increase in the width of the area of compression, on the one hand, reduces the minimum pulse duration attainable with a nonlinear PBG structure, on the other hand, lowers the group-velocity dispersion, which increases the compression length. It should be noted, however, that the inverse spectral width of the self-compression range gives only an estimate of the lower bound for the minimum pulse duration. In reality, this limit is difficult to achieve because of the simultaneous action of nonlinearity and higher order dispersion.

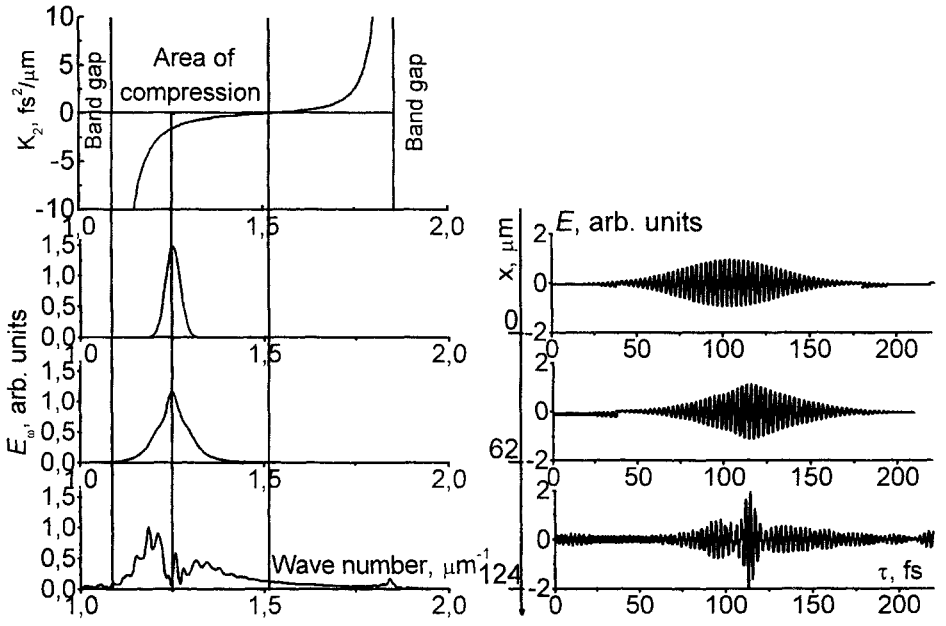

FIGURE 1. The evolution of the spectrum and the envelope of a laser pulse with a wavelength of 800 nm and initial duration $\tau_0 = 10T_0$ propagating in a one-dimensional PBG structure with $a = b$, $\varepsilon_{0a} = 1$, $n_0 = \sqrt{\varepsilon_{0b}} = 1.5$, $d = 415$ nm, and the intensity-dependent addition to the dielectric constant $\xi = \varepsilon_{nl}|E|^2 = 0.01$ ($\tau = \frac{X}{c} - t$). The dependence of parameter k_2 on the wave number and the frequency range where group-velocity dispersion of a PBG structure ensures self-compression of an SPM-chirped light pulse (i.e., condition (5) is satisfied) are shown at the top of the figure.

Numerical simulations also clearly demonstrate the influence of higher order dispersion, which may noticeably distort the waveform of a light pulse. Thus, parameters of a PBG pulse compressor have to be optimized in such a manner as to achieve a compromise between (i) minimum pulse duration and minimum compression length and (ii) maximum efficiency of pulse compression and minimum distortions of the pulse waveform.

Nonlinear FDTD simulations for a 800-nm laser pulse with an initial duration $\tau_0 = 10T_0$ propagating through an optimized one-dimensional PBG structure with $a = b$, $\varepsilon_{0a} = 1$, $n_0 = \sqrt{\varepsilon_{0b}} = 1.5$, $d = 438$ nm, and the intensity-dependent addition to the dielectric constant $\xi = \varepsilon_{nl}|E|^2 = 0.002$ demonstrate that such a nonlinear PBG structure can ensure efficient pulse compression. Similarly to the compression of chirped pulses in optimized linear PBG structures, the characteristic parameters of compression (viz., the minimum pulse duration and the compression length) in optimized nonlinear PBG structures agree well with estimates obtained within the framework of the second-order

dispersion theory for pulses with slowly varying envelopes. The characteristic nonlinear length in this approximation is estimated as $L_{nl} = \sqrt{L_d \lambda / \pi\xi} \approx 337$ μm ($L_d = \tau_0^2 / |k_2|$ is the dispersion length), and the relative spectral broadening is $\Delta\omega / \Delta\omega_0 = \sqrt{1 + \left(0.88 \pi\xi z / \lambda\right)^2} \approx 2.89$, which corresponds to compression of a pulse with $\tau_0 = 10T_0$ to $\tau = 3.45\ T_0$. However, this approximate approach cannot describe distortions of the pulse waveform and becomes inapplicable when the bandwidth of a laser pulse becomes comparable with the width of the compression range (see the dependence of k_2 on the wave number at the top of Fig. 1).

3. PHASE- AND GROUP-VELOCITY MATCHING IN SECOND-HARMONIC GENERATION

Improving the efficiency of nonlinear-optical interactions is one of traditional problems of nonlinear optics. Due to the rapid progress of femtosecond lasers, phase- and group-velocity matching of ultrashort laser pulses involved in nonlinear-optical wave mixing becomes one of the central issues on the agenda of this area of laser physics.

Some fundamental ideas on the advantages and limitations of using dispersion properties of one-dimensional periodic structures for phase matching nonlinear interactions were discussed by Bloembergen and Sievers [22] as early as 1970, long before the notion of photonic crystals was introduced. The authors of [22], in fact, proposed a new type of phase matching, where the dispersion of a periodic structure compensates for the dispersion of the nonlinear material, and pointed out that phase matching for a wave-mixing process where one of the waves propagates in backward direction (optical umklapprozess) can be achieved by transferring the difference of the momenta to a multilayer. These ideas have been shown to work very well not only in one [23 - 25], but also in two and three dimensions [26]. In particular, Golovan' *et al.* [24] demonstrated that the use of a periodic structure made of porous silicon with varying porosity enhances the efficiency of SHG in reflection geometry (Fig. 2a). New possibilities of using photonic band-gap (PBG) structures for efficient second-harmonic generation have been recently pointed out by Scalora *et al.* [13].

To illustrate the idea of phase and group-velocity matching of short pulses involved in second-harmonic generation in a one-dimensional PBG structure, we will consider a model infinite PBG structure described in Section 2. FDTD simulations demonstrate that such a model adequately reproduces the main properties of nonlinear-optical interactions involving very short pulses in periodic structures when the number of field cycles in the pulse is much less than the number of periods in the PBG structure. We assume that the layers of the PBG structure with refractive index n_a are neither

dispersive nor nonlinear, while the layers with refractive index n_b possess both dispersion and a quadratic nonlinearity, leading to second-harmonic generation.

To phase-match SHG in such a structure, we have to satisfy the condition

$$k(2\omega) = 2k(\omega) \quad (6)$$

for the wave vectors at the fundamental and second-harmonic frequencies.

Temporal walk-off effects can be avoided if the group velocities of the fundamental and second-harmonic pulses are equal to each other,

$$\left.\frac{\partial k(\omega)}{\partial \omega}\right|_{\omega=\omega_0} = \left.\frac{\partial k(\omega)}{\partial \omega}\right|_{\omega=2\omega_0}. \quad (7)$$

Solving equations (6) and (7) involving the wave vectors and their frequency derivatives calculated from (3) for the fundamental and second-harmonic frequencies with respect to the parameters a and b for given values of the refractive indices at the fundamental frequency and the frequency of the second harmonic, we can find conditions when phase- and group-velocity matching can be simultaneously achieved for SHG in a 1D PBG structure. Obviously, not all the values of the refractive indices allow the transcendental set of equations (6) and (7) to be resolved. In particular, it can be easily verified that no phase matching can be achieved for SHG in a dispersive nonlinear 1D PBG structure if the linear subsystem of the 1D PBG structure consists of a set of half-wave plates.

Physically, phase- and group-velocity matching for SHG in a 1D PBG structure is achieved, of course, due to the compensation of the material dispersion by the dispersion of a periodic structure. Therefore, the increasing dispersion of the nonlinear medium would require higher and higher refractive index ratios for the compensation of the phase mismatch and group delay.

Calculation of the amplitude of the second harmonic produced through the SHG process in a 1D PBG structure is a rather complicated problem requiring numerical simulations. In [14], this problem was solved with the use of the FDTD technique. The results of FDTD simulations are generally consistent with the predictions based on the qualitative analysis presented above. At the same time, FDTD simulations allow the influence of pulse duration and high-order dispersion effects on the SHG efficiency to be revealed. In particular, as can be seen from Fig. 2b, when phase- and group-velocity matching is achieved for SHG in a dispersionless medium, the SHG efficiency remains a nearly quadratic function of the length of the structure within the propagation lengths corresponding to $1–10^3$ periods for pulse durations no less than ten field cycles. For shorter pulses, the spectrum may become to broad to fit the allowed range of photon energies, and higher order dispersion effects may considerably distort the pulse.

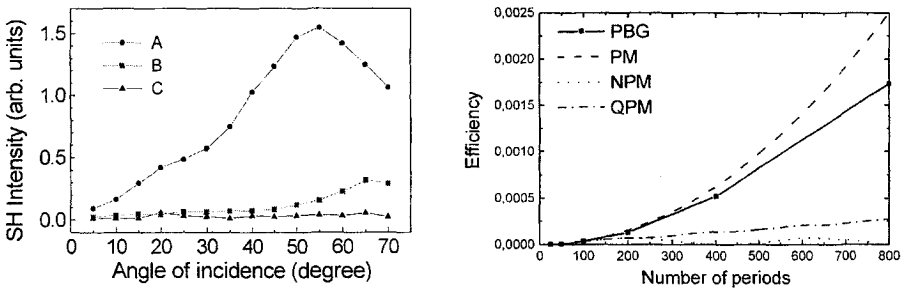

FIGURE 2. (a) The dependence of the second-harmonic intensity on the incidence angle of pumping radiation on porous-silicon samples with different parameters [25]. (b) The efficiency of SHG calculated [14] as a function of the nonlinear length for a PBG structure (solid line), QPM structure (dash-dotted line), and a nonlinear medium with phase and group-velocity mismatch (dotted line). The dashed line corresponds to the quadratic dependence of SHG efficiency on the interaction length.

Phase and group-velocity matching in PBG structures radically differs from quasi-phase matching (QPM) [27] in periodically poled structures [28]. While QPM is achieved due to the inversion of the sign of the quadratic nonlinearity on a characteristic spatial scale on the order of the coherence length (the dash–dotted line in Fig. 2b), phase and group-velocity matching in PBG structures is achieved due to the modulation of the refractive index with a characteristic spatial scale less than the optical wavelength, which allows high efficiencies of SHG to be achieved in the bulk of a nonlinear material regardless of its coherence length.

Extending the idea of PBG dispersion control to two and three dimensions provides much broader opportunities for the phase matching of nonlinear-optical interactions. As demonstrated in [29, 30], a light field can be localized within a subwavelength area in the defect mode of two-dimensional PBG structures, allowing the efficiency of wave mixing to be considerably increased.

4. FIELD LOCALIZATION IN TWO-DIMENSIONAL PBG STRUCTURES

FDTD analysis reveals several important features of light propagation and localization in a two-dimensional (2D) PBG structure with a defect. FDTD simulations were performed [29, 30] for macroporous-silicon 2D PBG structures consisting of five to ten periods of cylindrical air holes arranged in a triangular lattice in silicon irradiated with a plane light wave coming from $X = -\infty$. The ratio of the hole diameter to the lattice period along the Y-axis a was chosen equal to 0.95 in order to ensure the maximum width of the band gap for the considered macroporous-silicon structure. A

defect was introduced into the 2D PBG structure considered above by removing one of the rows of air cylinders periodically (with a period Λ) along the Y-axis, which allowed us to use periodic boundary conditions along the Y-axis with a period Λ. In order to suppress reflections from artificial boundaries, we employed standard absorbing boundary conditions while simulating light propagation along the X-axis by assuming that absorbing surfaces are located at $X = -5a$ and $X = 23a$.

Numerical analysis reveals several important features of light localization in PBG structures [29, 30]. In particular, the localization of light within areas whose sizes are less than a wavelength (Fig. 3a) suggests that a subwavelength resolution can be achieved with PBG structures. FDTD simulations demonstrate that an evanescent field can be efficiently generated with the use of PBG structures (Fig. 3b), offering the way to achieve the subwavelength (on the order of $\lambda/10$) spatial resolution in the scheme of near-field optical microscopy and allowing us to propose PBG structures as components of near-field optical microscopy. A probe object with a size less than the wavelength of incident light perturbs the near-field distribution behind the PBG structure due to the optical tunneling effect and changes the optical signal detected in the far-field zone. The field intensity distribution inside the PBG structure responds to the presence of a probe object by a decrease in the field localization degree, showing the way to control the light field localized in defect modes of PBG structures [29, 30].

Since the energy at the output of a photonic crystal with a defect is high enough, evanescent waves produced with a PBG defect mode can be employed not only in near-field microscopy, but also for creating subwavelength features in photolithography, increasing the density of optical data storage in one, two, and three dimensions (the absence of cross talk between neighboring defects in a PBG structure is especially important in this case), visualizing the propagation mode in waveguiding systems, producing local excitations in samples, and fabricating subwavelength planar integrated-optics components.

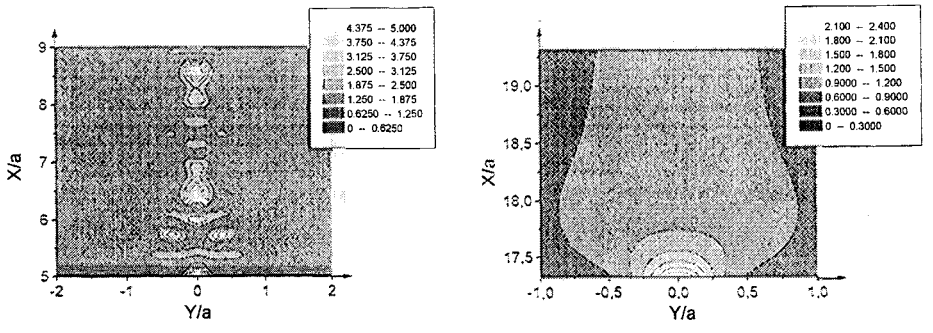

FIGURE 3. Two-dimensional maps [30] of (a) light localization (field intensity distribution) in a PBG structure and (b) the field intensity distribution at the output of a 2D PBG structure with a defect. Gray-scale levels represent the mean values of the electric field squared.

5. PHOTONIC-CRYSTAL FIBERS WITH A PHOTONIC BAND GAP TUNABLE FROM 930 TO 1030 nm

Many of the ideas proposed in the physics of photonic crystals can be extended to the optical range by using a concept of optical fibers with a photonic-crystal cladding, called also holey fibers [31 – 39]. The cladding in optical fibers of this type has a structure of a 2D PBG structure, i.e., consists of a two-dimensional periodic array of closely packed hollow silica fibers. A fiber without a hole serves as a core in such a waveguide. Knight *et al.* [31] were the first to fabricate holey fibers and investigate their main properties. These studies have demonstrated that waveguides with a photonic-crystal cladding support a single-mode propagation regime within a broad spectral range, allowing radiation energy losses to be considerably reduced and the effective area of the waveguide mode to be substantially increased. The results of these experiments stimulated intense investigations into the waveguide properties of holey fibers, which allowed the mode structure of radiation in such fibers to be revealed [32], the boundaries of the single-mode regime to be found [33], and the frequency dependence of laser-radiation divergence to be determined [34]. Along with exciting and important applications related to the control of light propagation, PBG fibers hold much promise also for nonlinear-optical applications. In particular, the high localization degree of light field in the core of a holey fiber suggests the way to improve the efficiency of nonlinear-optical interactions in such materials [36]. Recent experiments [37, 38] have shown that these properties of holey fibers can be employed to control the spectra of ultrashort laser pulses (Fig. 4) and to generate a supercontinuum.

The investigations of waveguiding properties of holey fibers have been restricted until recently to propagation regimes when the radiation wavelength is much less than the pitch of the photonic-crystal cladding and the core diameter. In this regime, the existence of a photonic band gap has, in fact, no influence on the propagation of light in a fiber. The possibility of creating holey fibers with a pitch of the PBG cladding less than 500 nm, displaying a photonic band gap of the cladding within the wavelength range typical of widespread lasers has been demonstrated recently in [39].

The periodic structure in the cladding of a holey fiber (Fig. 5a) gives rise to photonic band gaps in the transmission spectrum of the structure measured in the direction perpendicular to the direction of waveguiding. Two-dimensional periodic structures with a period less than 500 nm (the technology for the fabrication of such structures is described in [37]) allowed us to observe photonic band gaps within the wavelength range characteristic of widespread lasers. Transmission spectra measured for a holey fiber with a period of the PBG structure less than 500 nm are presented in Fig. 5b. The photonic band gap in the transmission spectra of such samples was observed within the range of wavelengths from 930 to 1030 nm. Since air holes periodically arranged in the fiber cladding form a hexagonal lattice, the position of the photonic band gap in the transmission spectrum changes, as can be seen from Fig. 5b, depending on the rotation angle of the structure with respect to incident radiation.

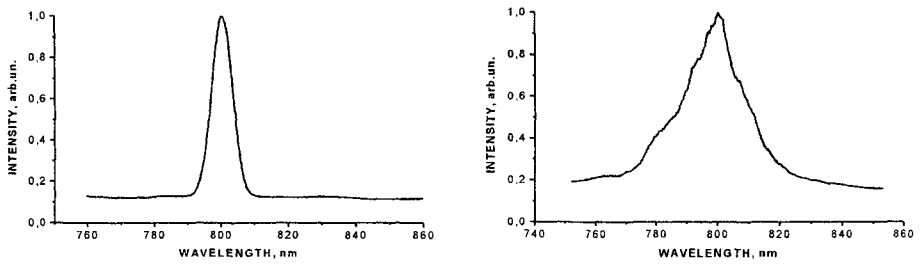

FIGURE 4. Spectral broadening of a femtosecond light pulse in a holey fiber [37]: (a) the spectrum of a 150-fs Ti: sapphire laser output pulse and (b) the broadened spectrum of the pulse at the output of the holey fiber with a pitch of the PBG cladding equal to 1.7 μm. The insets show the images of the beam patterns recorded by the CCD camera, with the horizontal direction corresponding to the spatial beam profile and the vertical direction corresponding to the spectral profile.

The structure of the photonic band gap in the transmission spectrum of a photonic-crystal structure depends on the ratio of the refractive indices of materials forming the structure. In the case of holey fibers, this circumstance opens up the opportunity of tuning the photonic band gap by filling the air holes in the PBG structure with various materials whose refractive indices differ from unity.

We have studied changes in the photonic band gap of holey-fiber samples arising when the air holes of the structure were filled with alcohol. As can be seen from the results presented in Fig. 5b (curves *4–6*), the position and the width of the photonic band gap noticeably change in this case.

Thus, holey fibers with a period of a photonic-crystal structure in the cladding less than 500 nm allowed us to demonstrate the existence of a photonic band gap within the 930–1030-nm wavelength range in the transmission spectra of such structures measured in the direction perpendicular to the direction of waveguiding. Holey fibers with a photonic-crystal cladding displaying photonic band gaps within the range of wavelengths characteristic of widespread laser sources seem to offer much promise for increasing the field-localization degree in the fiber core, thus opening new horizons in increasing the efficiency of nonlinear-optical processes, phase-matching nonlinear-optical interactions, and producing ultrashort laser pulses. The tunability of the photonic band gap of a photonic-crystal cladding in holey fibers offers broad opportunities for tuning the dispersion of holey fibers and controlling the luminescence of molecules within a broad spectral range.

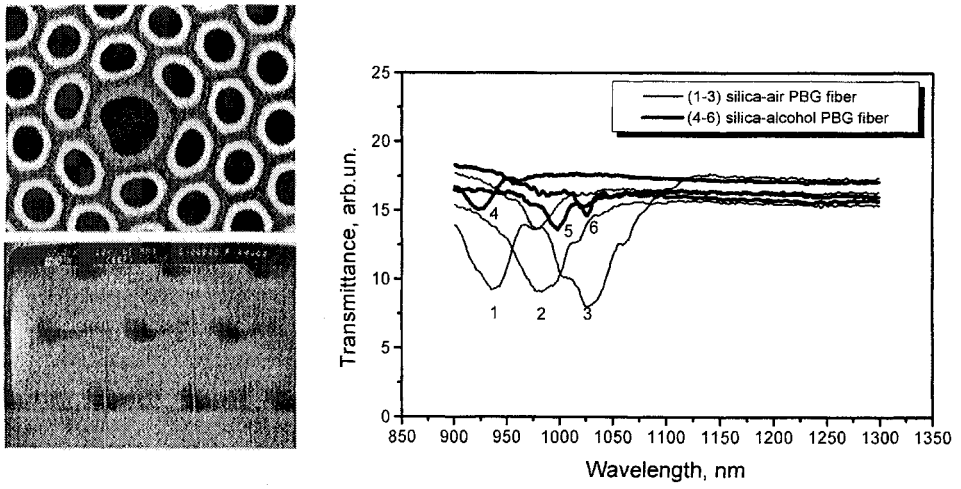

FIGURE 5. (a) Conventional-microscope (top) and SEM (bottom) images of photonic-crystal cladding of a holey fiber with a pitch of (top) 32 μm and (bottom) 468 nm. (b) Tuning the photonic band gap in transmission spectra of the photonic-crystal cladding of holey fibers: Transmission spectra of a photonic-crystal fiber measured for different directions of the wave vector within the first Brillouin zone of the photonic-crystal cladding for (*1–3*) silica–air and (*4–6*) silica–alcohol PBG structures.

6. CONCLUSION

The format of this lecture allows us to give only a brief introduction into the ultrafast optics of photonic crystals, providing only a general impression of how photonic crystals can help to control the parameters of short light pulses and light beams. However, the examples considered above demonstrate us very clearly that photonic crystals can be considered as promising elements for modern optical technologies, permitting a considerable conceptual progress in designing compact frequency converters and pulse compressors, new types of waveguides, and elements for local photoexcitation and high-resolution microscopy. Remarkable properties of field localization, confinement, and enhancement characteristic of photonic crystals can be employed to increase the efficiency of nonlinear-optical interactions of short light pulses and to guide laser beams. Properly engineering the photonic-crystal lattice, one can often construct a potential required for the solution of many problems of classical and quantum electrodynamics, including the laser guiding of atoms and the entanglement of quantum states. These and many other useful applications of photonic crystals call for the development of new technologies for the fabrication of three-dimensionally periodic structures with a photonic band gap in the visible range and elaboration of new efficient methods for the analysis of temporal and spatial properties of light fields in such structures.

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